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MAGNETIC SUSCEPTIBILITIES[1]

A. Classification of Bodies, Magnetically.—1. Let us assume that we have at our disposal a *uniform* magnetic field whose intensity, H, and direction we can vary at will. H will be expressed in Gauss and may be graphically represented by drawing through a unit area a number of parallel lines numerically equal to H. Into such a field of force we may introduce any substance we wish and study the effects which that substance may produce on the number of lines of force which thread through the space we call the magnetic field. Experimentally we find that any substance when brought into a uniform magnetic field causes a perturbation of the lines of force, the character of which separates all substances into two classes, viz., dia- and paramagnetic bodies. The lines of induction are a continuation of those of the field, but in the case of a paramagnetic substance are more closely packed together, while in a diamagnetic body they are further apart. Ferromagnetic substances are special cases of paramagnetism of which the lines of induction are, relatively, very closely packed together. A comparison with the electric currents would make this idea more precise.

Suppose a sphere of metal introduced into a mass of mercury traversed by a uniform current: the lines of flow which were originally parallel would tend to pass in greater number through the sphere if it were a better conductor than the mercury, and, on the contrary, in smaller number if it were a worse conductor. The words conductivity for lines of flow and permeability for lines of magnetic induction thus correspond to analogous ideas.

If we let B represent the number of lines of induction threading through unit area in

[1] Read before a joint meeting of the American Physical Society and Section B of the American Association for the Advancement of Science, December, 1920.

the substance, placed in a magnetic field of strength, H, then we have the relation existing between these quantities given by the equation

$$B = H \pm 4\pi I. \quad (1)$$

The number of lines of force which thread out from a magnetic pole is $4\pi m$. In equation (1) B is less or greater than H as I is negative or positive. That is to say, there is developed at opposite ends of the specimen placed in the magnetic field, H, a polarity which in case of paramagnetic substances is additive to H and makes B greater than H while in diamagnetic substances an opposite polarity is developed whose field subtracts from H and makes the resultant lines of induction further apart than the lines in the field of force. I, therefore, may be defined as the pole strength per unit area of the pole developed in the specimen, or it is the intensity of magnetization of the material examined. More frequently I is defined as the magnetic moment per unit volume, for if we take a cylinder of any material and place it in a magnetic field, then $Al = M$, the magnetic moment of the cylinder, where A is the crossection and l is the length of the cylinder. $I = M/Al = M/V$, or the magnetic moment per unit volume. It is assumed that the poles are at the ends of the cylinder. Next divide equation (1) by H and we get

$$\mu = 1 \pm 4\pi k, \quad (2)$$

where μ is called the permeability, and k the susceptibility. $\mu = B/H$ is a measure of the power the substance has for increasing the external field. This is a quantity in which the electrical engineer is particularly interested. Further, $k = I/H$ seems also to be a factor due to properties inherently bound up with the substance introduced into the magnetic field. This factor k is called the magnetic susceptibility per unit volume. In order to get the susceptibility per unit mass we must divide the volume susceptibility by the density of the substance. As k is negative or positive so is a substance dia- or paramagnetic. It is a property in which physicists must be vitally concerned in building up a magnetic theory and developing comprehensively the architectural design of the atom. Before we have finished this discussion we must ask the question, where does the property of susceptibility lie—in the electron, atom, molecule or aggregation of molecules?

2. Next let us work with a non-uniform magnetic field such as one has between the conical pole-pieces of an electromagnet and let us give definite shape to the samples of the various materials investigated, viz., ellipsoidal form. This time we will observe the behavior of the specimens as the magnetic field is applied to them. Experimentally, we discover that here again all substances divide themselves into two groups; one class turns in the magnetic field so as to set the greatest length normal to the lines of force of the magnetic field and the other class with major dimensions parallel to the field. Not only that but those substances which set themselves normal to the field are just those which we call diamagnetic in our first experiment and those which turn with greatest length parallel are the paramagnetic elements, which also include the ferromagnetic substances. Thus we have another way in which to distinguish dia- from paramagnetic substances. It is to be noted that in a uniform magnetic field all elongated bodies set themselves parallel to a magnetic field. The reason for the orientation cited above for diamagnetism is because the poles of the substance tend to move from stronger to weaker fields.[1a]

3. As a third experiment let us work with a non-uniform magnetic field in which the variation of the field along any direction is known. Introducing our samples in the form of spheres into this field we note that they all tend to move in one direction or the other in the field, either from a point of large field intensity to one of lower or vice versa. As in our previous observations there are two classes and we find that diamagnetic substances always move from higher to lower field intensities and paramagnetic are urged in the opposite direction. Ferromagnetic bodies

[1a] Poynting and Thomson, *Elec. and Mag.*, p. 258, 1914.

distinguish themselves by their energetic paramagnetic action in the magnetic field.

The foregoing may be summed up by the following:

TABLE I.

Diamagnetic substances, μ less than unity, k negative and does not vary with H.

Paramagnetic substances, μ small but greater than unity, k positive and does not vary with H.

Ferromagnetic substance, μ greater than unity and varies with H, k positive and a complicated function of H and T.

This is practically the state of knowledge in which Faraday, Plücker, Becquerel and others left this field of knowledge fifty years ago.

B. Modern Theories of Dia-, Para- and Ferromagnetism.—The electron theory forms the basis of the modern theories of magnetism which took their rise from an extensive investigation made on the magnetic properties of bodies by Professor Curie,[2] whose name is mainly associated with the discovery of radium. Yet in this field, which we are discussing, Curie's name must always stand forth as one of the pioneers.

Based largely on Curie's work Langevin[3] has built up a theory of dia- and paramagnetism which has been extended to ferromagnetism by Weiss.[4] These theories have been of value in that they have led to new experimental evidences concerning the behavior of substances magnetically, so that in our discussion these three names, naturally, will receive more attention than others, although the contributions of others are exceedingly important. Among others to be mentioned are Honda, K. Onnes, Dewar and Fleming, Oosterhuis, Pascal, Oxley, Kunz and Owen.

In a long and careful series of investigations, Curie observed the behavior of various substances when placed in a non-uniform magnetic field, in which the observations were extended over a wide range of field intensities and temperatures. Figures illustrating the apparatus used will be found in the original articles. The range of field strengths was from about 25 to 1,500 c.g.s. units and of the temperature from about 22° C. to 1350° C. His results are generally expressed in terms of mass susceptibility where k is positive when the substance moves toward more intense field strengths and negative when oppositely drawn. Curie examined a series of substances in each of the three groups, dia-, para- and ferromagnetic materials.

1. *Diamagnetic Substances.*—Rock salt, quartz, water, KCl, K_2SO_4, KNO_3, S, Se, I, Br, Te, P, Bi, and Sb were the substances studied. Special attention was paid to water in order to determine k absolutely as a standard of reference. Bismuth showed remarkable properties as it passed through its melting point. In every case k was independent of H and with the exception of three all gave a value of k independent of temperature and of physical state.

2. *Paramagnetic Substances.*—Air, palladium, $FeSO_4$ in aqueous solution, oxygen, glass and porcelain were the subjects investigated. Glass and porcelain were studied because they were used as the material for the container in which to test gaseous and other forms of materials. The other four paramagnetic substances were found to have a susceptibility independent of field strength and satisfied the condition that k varies as $1/T$. Beside the work on $FeSO_4$ in water Curie tried also the magnetic salts of Co, Mn and $NiSO_4$. The first two fitted in with the general law but $NiSO_4$ showed too rapid a change in its susceptibility for the inverse temperature law. The second law of Curie that k varies as $1/T$ may be expressed by saying that $kT =$ a const. which has become known as Curie's constant.

3. *Ferromagnetic Substances.*—Curie investigated nickel, soft iron, magnetite and cast iron. He paid particular attention to soft iron, studying the variation of I with T when H was maintained constant and again the variation of I with H when T was kept constant. For a certain range of temperature above the critical temperature of magnetic

[2] Curie, *Ann. de Chim. et de Phys.*, 5, 289, 1895.

[3] Langevin, *Ann. de Chem. et de Phys.*, 4, 70, 1905; *Jour. de Phys.*, 4, 678, 1905.

[4] Weiss, *Jour. de Phys.*, 6, 661, 1907; *Comp. Rend.*, 152; 79, 187, 367, 688, 1911.

transformation, the substances just listed behaved as paramagnetic materials in that I was independent of H and $k \propto 1/T$. As the temperature falls there is continuity in passing from the paramagnetic state to the ferromagnetic state. No such continuity, however, seems to exist when one passes from the paramagnetic to the diamagnetic state, which suggests that the causes underlying the two states are quite different. So far this discussion has been largely historical and is given to serve as a background for a further discussion of the theories of Langevin and Weiss which have grown out of the researches of Curie.

Curie's work seemed to indicate that paramagnetic substances would give infinite susceptibility at absolute zero. This phase of the subject has been very extensively studied. Dewar and Fleming[5] found for solid $MnSO_4$ and liquid oxygen that it did hold down to $-186°$ C. On the other hand the work of K. Onnes and Perrier,[6] Oosterhuis[7] and Honda[8] and Owen[9] seemed to show that Curie's second law is not at all true for the majority of paramagnetic substances and that furthermore a great many diamagnetic elements disobeyed the first law, viz., that they did not maintain a constant susceptibility as the temperature changed. Tables X. and XI. in the excellent paper of Dushman[10] show these discrepancies in a very striking way. These results have led Kunz[11] to remark that,

> It seems to me not justified to maintain Curie's rule, as there are many more exceptions than confirmations. The same is true for diamagnetism. . . . There are only very few elements which do not vary within the whole temperature range.

This weakens the foundation on which Langevin and Weiss build their theories for dia-, para- and ferromagnetism. The multitudinous works of those already mentioned with a host of others make it all too apparent that the phenomena of magnetism are exceedingly complicated. We must not, to quote Stradling,[12] expect too much of any explanation in view of the apparently contradictory facts. The theoretical and experimental investigations of Langevin and Weiss have been very productive of further experimental work and theory so that they must hold a very important place in the future development of magnetic theories. I can do no better than use the method of presentation given in the excellent résumés of the work of these two men which have been made by various English and American writers.

1. *Langevin's Theory of Diamagnetism.*—To begin with it is to be recalled that Rowland first demonstrated the fact that a moving charge created a magnetic field; if the charge moved in a circular orbit a magnetic field was produced normal to the plane of the path in which the charge moved. This forms a picture of electronic orbits which we suppose to exist in the flame for the Zeeman effect. If a magnetic field is thrown on to a group of such revolving charges, differences in period of revolution will be produced, in some cases decreasing and in others increasing the period. This gives rise to the double and triple lines which we see in the field of view of the spectroscope. This behavior of electronic orbits lies at the foundation of Langevin's and Weiss's theories. Thus according to Langevin if we introduce a substance into the magnetic field which is diamagnetic according to the tests we have already described, then the electronic orbits which we suppose surround every atom will be affected in the way we have just described them as being influenced in the Zeeman effect: some will have their periods decreased and others in-

[5] Dewar and Fleming, *Proc. Roy. Soc.*, 60, 57, 1897; 63, 311, 1898.

[6] Onnes and Perrier, Comm. No. 139a, Phy. Lab. Leiden. (See article Oosterhuis, *Koninklyke Akad.*, Amsterdam, 16, 892, 1913–14.)

[7] Oosterhuis, *Proc. Amsterdam Acad. Sci.*, 16, 432, 1913–14. (Look up bibliography contained in this volume of the *Proceedings.*)

[8] Honda, *Ann. d. Phys.*, 32, 1910.

[9] Owen, *Ann. d. Phys.*, 37, 657, 1912.

[10] Dushman, Reprint, *Gen'l. Elec. Rev.*, May, Aug., Sept., Oct. and Dec., 1916.

[11] Kunz, Eighth Internat. Cong. App. Chem., 22, 187, 1912.

[12] Stradling, *Journ. Franklin Inst.*, 180, 173, 1915.

creased. If the atom is built so that there are a number of electronic orbits so oriented that their resultant magnetic moment is zero then there will be no tendency for the atom as a whole to rotate, but on the application of the magnetic field there will be a tendency to alter the magnetic moment of each electronic orbit and no matter in which direction the electron is revolving the effect of the magnetic field is to create a polarity opposed to that of the applied field. If the magnetic moment of one electronic orbit is positive the effect of the external field is to decrease it and if the magnetic moment of another orbit is negative the external field acts to increase it so that the total effect is the same as that which we get from Weber's[13] theory of diamagnetism which assumes that there are no revolving electrons present to begin with but when a diamagnetic substance is exposed to a magnetic field, currents are set up in the atoms or molecules which develop magnetic fields having an opposite polarity to that of the inducing field. If the orbits of these circuits are resistanceless the currents will be maintained until the magnetic field is withdrawn again. It is to be noted that in the case of diamagnetic substances a finite magnetic moment is developed in the elementary unit with which we are dealing and which ought to have a corresponding tendency to rotate in a magnetic field. This point does not seem to be emphasized in the theory of diamagnetic substances, but as we shall see later on it is stressed in paramagnetic bodies. We know that an elongated portion of a diamagnetic substance does orient itself very definitely in a magnetic field. From the standpoint of the theory of diamagnetism just reviewed, diamagnetism must be almost a universal property of matter because we find the Zeeman effect in nearly all spectral lines of nearly all substances. We believe that the hydrogen atom has only one electronic orbit. Its diamagnetism is difficult to explain by Langevin's theory.

[13] Dushman, *Gen'l Elec. Rev.*, p. 20 of reprint from May, Aug., Sept., Oct., and Dec. issues, 1916.

2. *Langevin's Theory of Paramagnetism.*—

We have seen that in all cases the creation of an exterior magnetic field modifies the electronic orbits by polarizing diamagnetically all the molecules.

If the resultant moment is not zero, upon the diamagnetic phenomena is superimposed another phenomenon due to the orientation of the elementary magnets by the external field. The substance is then paramagnetic if the mutual action between the elementary magnets is negligible, as in the case of gases and of solutions and ferromagnetic in the case where the mutual actions play the essential rôles. As soon as the paramagnetism appears it is, as a rule, enormous in comparison with the diamagnetism and therefore completely conceals it. This explains the discontinuity between paramagnetism and diamagnetism; paramagnetism may not exist; but if it does, it hides completely the diamagnetism.

Therefore, substances whose atoms have their electrons in revolution in such a way that their effects are additive, are paramagnetic. The atoms of such substances may be looked upon as elementary magnets.

If we think of the elementary magnets at ordinary temperatures as being in a state of agitation then the tendency of the elementary magnets to orient themselves in a magnetic field will be opposed by the thermal agitation of the elementary magnets and they will settle down under a state of statistical equilibrium.

3. *Weiss's Theory of Ferromagnetism.*—Langevin has given a theory of dia- and paramagnetism and largely assumes ferromagnetism as a special case of paramagnetism. That ferromagnetism is a special case of paramagnetism will, I think, be conceded by all, but to explain more completely the phenomena attendant on ferromagnetism, Weiss has extended the theory somewhat by saying that to explain the varied phenomena as we find them, there must be associated with the turning of the elementary magnets something which acts like an extra magnetic field in addition to the external field applied. After considering all phases of the problem, however, and showing that he can explain many of the existing phenomena by means of this extra or intrinsic molecular field he is forced to admit that this "molecular field must be attributed to the

action of forces whose nature is still unknown." What must be the nature of these forces between elementary magnets? Weiss argues that they are neither magnetic nor electrostatic. These are questions to be left to the reader.

An attempt to correlate the many researches which have followed in the wake of Curie, Langevin and Weiss leaves the reviewer with a feeling of utter helplessness. The experimental work, in many cases, might well serve as examples of the highest type of modern physical research, but, when it comes to the various theories advanced, one must confess to a feeling that it is a good guessing contest in which one is as good as the other.

Out of Weiss's work, however, has grown a conception that seems destined to have some real meaning as we learn more concerning magnetic phenomena, that is, the magneton. Just as we have found that the electron seems to be the unit out of which we build all other electrical charges so here Weiss finds a similar analogy in that the magnetic moment per gram molecule of various substances seems to be small multiples of a common magnetic moment, equal to 1,132.5. Since we think of magnetic fields as due to moving charges can the magneton ever be so fundamental a concept as is the electron?

C. Seat of Magnetic Powers.—As we go over these various theories one is impressed by the recurrent words, orientation, rotation, revolution, change in magnetic moment, electronic orbits, etc., and then one begins to wonder as to how much magnetic phenomena really depend on these phases of the subject.

1. When a piece of iron, nickel or cobalt is placed in a magnetic field, what grounds have we for saying that the molecules, atoms or elementary magnets of the specimen are actually turned in situ by the external magnetic field? Does our affirmation of this question rest upon the fact that Ewing[14] once on a time pivoted a number of little magnets on needle points and showed how they behaved in a magnetic field and said this is the picture of a group of elementary magnets? Small magnets will turn on axes as Ewing showed they would and the logic is that the elementary magnets will also, but note that Ewing would have found hysteresis and B-H curves even if his little model magnets had not turned at all. Ewing's magnets did turn and the logic of the argument has tremendous confirmation in the work of Swinburne[15] who predicted as a consequence of Ewing's theory that if a piece of iron is rotated in a very strong magnetic field and the elementary magnets are held in alignment steadily as the iron cylinder is rotated there will be no changing from one configuration to another which may be unstable and thus dissipate magnetic energy into vibrational energy; consequently there will be a suppression of hysteresis. This was experimentally confirmed. Another verification is found in the experiment of Waggoner and Freeman[16] on the suppression of hysteresis by a longitudinal A.C. magnetic field, where the same kind of explanation as Swinburne's might be applied. This suppression of hysteresis seems to be closely associated with a certain degree of freedom to rotate, as for instance Rosenhain[17] points out that when an element whose atomic volume is greater than that of iron with which it is alloyed, the effect of the added element is to decrease the hysteresis. The increased atomic volume, from a mechanical viewpoint, makes larger interstices between the elementary magnets which permits of greater freedom to swing. If we have a theory to explain dia-, para- ferromagnetism then that same theory, in order to be a comprehensive magnetic theory, must explain all magnetic phenomena. At this point an outline might be introduced as an aid to keeping one's bearing when dealing with general magnetic phenomena.

[14] Ewing, *Magn. Induc. in Iron*, etc., p. 348 et seq., 3d ed.

[15] Swinburne, Baily, *Phil. Trans.*, 187, 715, 1896.

[16] Waggoner and Freeman, *Gen'l Elec. Rev.*, p. 143, Feb., 1918.

[17] Rosenhain, "Introduc. to Phys. Metallurgy," p. 110, 1915.

TABLE II

I. Induction Effects.
   1. Relation between field strength and magnetic induction, permeability, susceptibility, coercive force, retentivity, hysteresis, etc.
   2. Dia-, para- and ferromagnetism.
   3. Terrestrial magnetism.
   4. Alternating currents.
   5. Inductive effects as influenced by temperature, mechanic strains, aging, etc.
   6. Relation between susceptibility and chemical properties.

II. Mechanical Effects.
   (*a*) Reaction effects between magnetic fields.
      1. Attraction and repulsion of magnetic poles.
      2. Motion of electric conductors, solids, liquids and gases, carrying currents when placed in a magnetic field.
      3. Hall effect and its reciprocal relations.
   (*b*) Magnetostrictive Effects.
      1. Joule effect. Its reciprocal relations.
      2. Villari effect.
      3. Wiedemann effect. Its reciprocal relations.
      4. Volume change. Its reciprocal relations.
      5. Change in resistance due to a magnetic field.
      6. Production of sound.
      7. Piezo- and pyromagnetism.
      8. Magne crystallic action.
      9. Effect of magnetic field on thermoelectric phenomena.

III. Magneto-optical Effects.
   1. Faraday effect.
   2. Kerr effect.
   3. Zeeman effect.
   4. Magnetic double refraction.

Naturally one might question some points in this classification. Certainly changes would be made if we knew more about the subject. Whatever the arrangement of subjects a complete magnetic theory must explain all of the above phenomena. This is a real task. In particular, the present magnetic theories sidestep those phenomena listed above as magnetostrictive effects, which as the outline indicates is about half of the various magnetic effects. If the rotation of the elementary magnets due to an external magnetic field explains ferromagnetism then one may properly ask if the rotation of the elementary magnets might not also explain the magnetostrictive effects because these effects appear in ferromagnetic substances. Poynting and Thomson[18] have called attention to the fact that these magnetostrictive effects are yet to be explained on the molecular hypothesis. They state,

> It would obviously require some further assumptions as to molecular grouping or as to molecular dimensions in different directions.

The latter assumption has been a suggestive one and some progress has been made along this line, many of the magnetostrictive effects may be explained as being due to the orientation of elementary magnets whose dimensions vary in different directions. The work of Barnett,[19] Einstein[20] and deHaas and J. Q. Stewart[21] favors the idea of an orientation of the elementary magnet. Indeed our evidence seems very strong that rotation of the elementary magnets due to an external field is a part at least of all ferromagnetic phenomena.

The brilliant and highly significant work of the two Comptons[22] and their co-laborers[23] on the problem of the ultimate magnetic particle has a very important bearing on this phase of our discussion. Their interpretation thus far seems to argue against anything turning due to an external field unless it be something inside of the atom. If it is something inside of the atom it would seem difficult to explain the Heusler alloys or that bulk iron is ferromagnetic; while ferrous sulphate is paramagnetic and potassium fer-

[18] Poynting and Thomson, "Elec. and Mag.," p. 201, 1914.

[19] Barnett, *Phys. Rev.*, 6, 240, 1915.

[20] Einstein and deHaas, *Verh. d. deutsch. Phys. Ges.*, 17, 152, 1915.

[21] Stewart, *Phys. Rev.*, 11, 100, 1918.

[22] Compton and Trousdale, *Phys. Rev.*, 5, 315, 1915.

[23] Compton and Rognley, *Phys. Rev.*, 16, 464, 1920.

rocyanide is diamagnetic. No cataclysm of the atom has occurred in these chemical changes. On the other hand if we turn to magnetostriction for help in interpreting the work of the Comptons and explain magnetostriction as due to the orientation of the elementary magnets it would appear that their negative results may be due to the fact that they worked at only one field strength, whose value is not given in their papers, and at that field strength the orientation had not proceeded far enough to give measurable effects. For instance, in the case of an iron rod, as the magnetic field strength is increased from zero upwards, the rod first elongates and then shortens, becoming shorter at high field strengths than in its virgin state. At that field strength where the length once more becomes equal to the original length, at that point one would expect negative results in the work of the Comptons. In iron this field strength is about at the point where saturation occurs. From the magnetostrictive viewpoint the Comptons should find maximum effects at those field strengths where maximum changes in length occur. The Comptons used magnetite which is quite different from iron in the manner in which its length changes in a magnetic field. Yamada found that at several hundred Gauss field strength, it was still increasing its length and no maximum attained. The question may legitimately be raised as to whether the orientation of the elementary magnets had been carried on sufficiently to give the Comptons the effects they were looking for. A further study of the Joule effect in magnetite is being started to throw more light on this subject.

2. Would negative electrons revolving in orbits or negative electrons rotating, à la Parson, alone suffice as a picture of the elementary magnet? The theories we have so far discussed seem to convey the idea that they would. Why not attribute magnetic phenomena to a positive nucleus spinning on its axis? Barnett's work indicates the negative charge as the portion of the elementary magnet which is in motion. This does not, however, debar the positive nucleus from contributing some part of that property which we know as susceptibility and which we have been discussing. In other words induction may be a part of the property of the nucleus and we shift at least a part of that property from the mass to the elementary magnet.[24] What is it that gives magnetic characteristics? These are questions which our general subject of susceptibility raises. There are a number of items which, as it seems, bear upon these queries. Maurain[25] deposited thin films of iron and nickel and found he had to have a certain thickness of film before he obtained definite magnetic properties. For iron this was 8.3×10^{-8} cm. and for nickel, 20×10^{-8} cm. Wilson[26] in measuring the magnetic fields in a rotating iron cylinder arrives at the size of a magnetic particle as 10×10^{-8} cm. which checks fairly well. Hull,[27] working on the X-ray analysis of iron and nickel finds the distance of 2.47 and 2.50×10^{-8} cm. respectively as the distance between nearest atoms. These values seem to be commensurate. As already pointed out the spacing of the atoms seems to play a very important part in magnetic phenomena. Hull calls attention to the fact that it might be anticipated that ferromagnetic substances would have the same crystal structure. This is not true for iron and nickel are different according to Hull's observations. It is evident that ferromagnetism does not depend upon any particular arrangement of atoms but more probably upon distance between atoms which would explain the fact that this property is lost when the temperature is increased beyond a definite value. A center cubic arrangement may be more favorable to ferromagnetism, but is not a principle or essential factor. Arnold and Hicks[28] state:

> The elements giving iron high permeability and

[24] *Phys. Rev.*, abstract, Feb., 1911. *Phys. Rev.*, 34, 40, 1912.

[25] Maurain, *Jour. de Phys.*, 1, 151, 1902.

[26] Wilson, *Proc. Roy. Soc.*, 69, 435, 1902.

[27] Hull, *Phys. Rev.*, 14, 540, 1919.

[28] Arnold and Hicks, *Nature*, Apr. 17, 1902.

low coercive force are those which cause it to crystallize in large crystals.

Aston[29] also says:

It seems true, other things being equal, that the heat treatment which will give to pure iron a coarseness of crystallization, and above all a uniformity and regularity of such structure will be accompanied by a low coercive force, and the effect of heat treatment is augmented by the addition of silicon or analogous elements, as arsenic or tin, all of which increase the coarseness of crystallization of the material.

It seems to be generally conceded that manganese is the essential constituent in the Heusler alloy. We don't know the magnetic properties of manganese any too well but its being associated so closely with iron, cobalt and nickel in the periodic system indicates the possibility of its possessing latent magnetism which under favorable conditions becomes active. Ross suggests that the presence of the other metals beside manganese exerts a helpful influence in making the manganese elementary magnets farther apart and so increasing its magnetic activity by the removal of the intense intermolecular forces which are supposed to act in the metal manganese. This point of view is further corroborated by the fact that the susceptibility of copper containing minute quantities of iron is far greater than that calculated from the amount of iron present. One of the most thorough researches undertaken on a phase of this subject was by Perrier and Onnes[30] who studied the susceptibility of a liquid mixture of oxygen and nitrogen and the influence of the mutual distance of the molecules of oxygen upon paramagnetism. In this work the oxygen at the low temperature is paramagnetic and inasmuch as the nitrogen did not enter into chemical combination with the oxygen it was possible to separate the oxygen molecules as much as desired by making the percentage of nitrogen larger. Their general results may be summed up by saying:

The specific magnetization coefficient of oxygen becomes considerably greater, in proportion as the concentration diminishes.

There is much to be investigated along this line.

This discussion leads inevitably to the question as to where we shall locate the origin of the property of susceptibility? Will a group of electronic orbits account for magnetic phenomena or must we have added to their effect that which arises from the positive nucleus? Could we have a group of small coils to replace the group of little magnets with which Ewing once worked and obtain results such as he did? I have been working on this problem the past two years and so far have not been able to realize experimentally what Ewing did. It must be emphasized again that Ewing in his classical experiments worked with elementary magnets in which each elementary magnet itself showed all the properties which the group did. An attempt to explain the magnetostrictive effects on a molecular hypothesis makes it look very much as though one needed another factor to add to the electronic orbit to explain that particular field of magnetic phenomena.

Space forbids to give all the reasons why one is led to think of the atom as the seat of the phenomena we meet with in magnetism, or that the atom is the elementary magnet. The classical argument against this point of view is that the iron atom is ferromagnetic, ferrous sulphate is paramagnetic and potassium ferrocyanide is diamagnetic. Iron is a constituent of all three. Why this wide divergence of property? From preceding arguments it would appear that interstitial relations might answer the question. Oxley[31] put it another way by saying, in speaking of diamagnetism, that the molecular structure is distorted by the near approach of the other molecular structures so that the self induction of the electronic orbits is affected. The magnetic theories of Langevin and Weiss are essentially atomic theories and that the susceptibilities of the elements is

[29] Aston, *Trans. Faraday Soc.*, Vol. 9, July, 1913.

[30] Perrier and K. Onnes, *Proc. Roy. Acad. Amsterdam*, 16, 901, 1914.

[31] Oxley, *Phil. Trans.*, 214 (*A*), 109, 1914.—215, *A*, 79, 1915.

related to the atomic numbers in a definite manner is brought out by the curve which Harkins[32] has worked out and in a more striking fashion the curve given by Dushman[33] relating the logarithms of the susceptibilities of the elements to the atomic numbers. The curves showing these relations indicate a very definite tie between them and yet there seems to be no other properties associated with atomic numbers which are definitely related to the susceptibilities of the elements. May not this fact also emphasize the importance of placing some of the magnetic properties of the elements in the nuclei?

To come back to the field of magnetostriction it would appear from its teaching that in addition to electronic orbits, to explain magnetic susceptibility, *there must be given to the positive nucleus of the atom a property of induction just as Ewing had in his elementary magnets, and, for ferromagnetic substances at least, these nuclei ought to have different dimensions in different directions, capable of being rotated by means of an external field.*

Helmholtz once said,

> The disgrace of the nineteenth century is our ignorance concerning magnetism.

What shall we say of the twentieth century?

S. R. Williams

Oberlin College,
Oberlin, Ohio

FUNDAMENTAL PRINCIPLES ESTABLISHED BY RECENT SOIL INVESTIGATIONS

INTRODUCTION

The following is a brief review of the fundamental principles established by modern methods of soil investigation in the Bureau of Soils in the past twenty or thirty years:

TEXTURE OF SOIL

The first step taken established the fact of the general influence of the texture of the soil and its water-holding capacity on the distribution of the great classes of crops; that is, the general relation between the sand, fine sand, silt and clay soils and the general distribution of areas devoted to the production of truck crops, corn, wheat, hay and other heavy farm crops. This together with field studies of origin, mode of formation, and observable physical differences led to the mapping of soils, or the soil survey, which has been extended over a considerable part of the United States.

With the wide field experience it became evident that differences existed between different soil types or in the same soil type that were not to be explained by differences in texture or in water-holding capacity, but that yields vary with the practise of the farmer or from other causes, as was fully known and commented upon by the early Roman writers, that would need to be explained before the practise of agriculture, the application of fertilizers, and the handling of soils could be put upon a truly scientific basis.

ORGANIC CHEMISTRY OF SOILS

The study of some notably infertile soils and of very productive soils of the same type which had been held under what we call "better systems of farming" revealed the presence of certain toxic organic compounds in the one which were not present in the other. This led to a study of the organic chemistry of the soils. Finally we succeeded in separating from soils some 35 definite organic compounds, some of which were beneficial to certain crops and some of which were toxic to certain crops and nontoxic to others. It was also found that soils under a certain condition of aeration would yield certain organic products and under other conditions of aeration other organic products. It was found that the compounds separated from the soil were of the same nature as the compounds in the digestive system and in the blood of man and animal and it was finally realized that the soil has a digestive system as it were and breaks down organic materials such as the proteins, carbohydrates, and fats much

[32] Harkins and Hall, *Journ. Amer. Chem. Soc.*, 38, 210, 1916.

[33] Dushman, *l. c.*